Advanced Optics Metrology

Program Manager: Christopher J. Evans
Total FTE: 3.45
Total Funding: $630,000

Goal

To develop optical figure, surface finish, and sub-surface damage measurement methods; to develop a metrological infrastructure to support advanced optical and semiconductor system fabricators; to develop measurement methods that users can implement to make traceable measurements in their own facilities without reference to any external authority; and to ensure the availability of traceable measurements.

Program Objectives

FY2000

Develop sub-surface damage assessment methodologies on sapphire using a variety of X-ray and optical methods.

Sub-surface Damage in Crystalline Optics

In collaboration with the Materials Science and Engineering Laboratory (MSEL), apply techniques for imaging sub-surface damage in sapphire domes and windows. Sources of sub-surface damage (SSD) will be identified. Where possible, damage detected before performance testing will be correlated with any failures that occur. The project will seek targets of opportunity to extend SSD activities to other materials.

FY2000

Support the Laser Interferometric Gravitational-wave Observatory (LIGO), National Ignition Facility (NIF), and National Aeronautics and Space Administration (NASA) large optics metrology programs through 2000.

Optical Measurement Services

Develop measurement procedures and apply them as needed to measure components for internal (NIST) and external customers, including NIF and NASA.

FY2001

Develop methods for reference measurements of wafer thickness, thickness variation, and bow based on infrared interferometry.

Optical Metrology of Wafers

Develop measurement methods for wafer thickness, thickness variation, and bow based on the NIST patented "Flatmaster" infrared (IR) interferometer. As-chucked wafer distortions will also be measured on XCALIBIR to provide metrology feedback for the development of improved wafer chucking methods.

FY2001

Develop generic uncertainty budget for interferometric measurement of radius of curvature.

Interferometric Measurements of Radius of Curvature

Develop a generic uncertainty analysis for radius of curvature measurement using a figure measuring interferometer and develop a calibration service for radius using XCALIBIR.

FY2001

Develop interferometric methods for quantifying striae in optical glass.

Interferometric Measurements of Striae

Evaluate new approaches to quantifying striae based on transmitted wavefronts.

FY2002

Develop a calibration service for flats, spheres, and aspheres based on the NIST X-ray Optics Calibration Interferometer (XCALIBIR).

Commission XCALIBIR

Complete XCALIBIR facility, qualify environmental control, and perform first "absolute" test of a flat and a spherical optic.

Optical Modeling of Figure Measuring Interferometers

Determine limitations in reduction of test uncertainty through ray-trace modeling of an optical test.

Customer Needs

Advanced optics represents a key enabling technology for a range of consumer and strategic applications. Next generation integrated circuits (estimated world market for integrated circuits in 2000 is $126 billion) will be made with ever shorter wavelength lithographic systems that, necessarily, have smaller depth of focus. The wafers, therefore, need ever-improved flatness on the chuck of the stepper or other tool, yet no traceable measurement system is in place. The optics themselves have finish specifications to spatial frequencies that mandate the use of scanned probe microscopies; no infrastructure exists to ensure that the measurements made are traceable. The Semiconductor Industry Association roadmap shows optical lithography continuing through the 157 nm generation. The follow on technology is not known, but the latest Next Generation Lithography workshop identified Extreme-Ultraviolet Lithography (EUVL — in which the U.S. has a clear lead) as a leading contender. EUVL operates at 11 nm to 13 nm, and demands optical figure metrology at sub-nm uncertainty; no such traceable measurements are available today. At these uncertainty levels, it is unlikely that a classic chain of traceability through transfer artifacts will be tenable; measurement methods must be developed to allow users to make traceable measurements in their own facilities without reference to external authorities.

In addition to surface figure, performance of refractive optics depends strongly on the index of refraction, and variants thereof, in the glass through which light passes. Current standards for high spatial frequency variations - known as striae - are based on visual inspection with respect to artifacts made at National Bureau of Standards (NBS) nearly a half-century ago. New methods are required.

Optical figure metrology is also an issue for a range of projects at the frontiers of science. The Laser Interferometric Gravitational-wave Observatory (LIGO), for example, uses optics with specifications close to those for EUVL. The National Ignition Facility (NIF), by contrast, will use 8000 large (400 mm +) optics and 30,000 smaller optics; validation of vendor metrology methods will eliminate the need for 100 % incoming inspection, but demands traceability and, hence, defensible uncertainty statements at every vendor.

NIST researchers provide a further customer base. Challenges recently addressed include the figure of long-radius spheres to be used in a hard X-ray Kirkpatrick-Baez imaging system and very small spherical optics for a Schwartzchild X-ray microscope.

Sub-surface damage (SSD) remains a problem throughout the optical fabrication industry, as well as in micro-electronic systems. No standards exist, nor even agreed terminology — yet the fear of SSD can drive fabricators to spend inordinate time in unnecessary finish. Meanwhile, SSD limits the performance of such components as missile windows and domes and has been implicated in unsatisfactory scatter and laser damage thresholds in other applications.

Technical Approach

The approach to measurement of optical figure is to use phase measuring interferometers (PMIs). Commercially available PMIs can be extremely repeatable; an array of techniques, including some developed in this program, are now available for separation of part errors from the signature of the instrument - at least for some classes of surface. Such approaches have shown that they can provide measurement uncertainties of the order of 1 nm for flats and near flats such as the LIGO optics. Higher uncertainties are obtained in the measurement of spherical optics. We will continue to develop measurement methods and error separation techniques to reduce the uncertainties of measurements made with commercially available PMIs. Also, we will develop techniques to allow users of such instruments to characterize their performance.

For the measurement of aspheric optics (i.e., systematic deviations from a base sphere), such as those needed for EUVL, there are some basic limitations to the potential of the commercially available PMIs. Concepts for a system combining a PMI with high precision slideways have been developed and implemented (in collaboration with an industrial vendor) in a new measurement capability, known as the NIST X-ray Optics Calibration Interferometer (XCALIBIR). The goal is 0.25 nm rms uncertainty in measurement of aspheric optics up to 300 mm diameter with focal lengths up to 2 meters. XCALIBIR — designed to have the flexibility to measure flats, spherical, and aspheric optics - was installed at NIST in the fourth quarter of FY99 (fiscal year 1999). A calibration service will be developed based on this capability.

Interferometric tests can be used not only to measure departure of the surface from the best-fit sphere, but with some adaptation, the radius of curvature of that sphere. Currently NIST offers no measurement service for radii and there is no rigorous analysis in the literature to help instrument users assess uncertainties in their own measurements of radius. XCALIBIR will be used to address these problems. In one of its operating modes, XCALIBIR offers testing at high spatial resolution in a plane wave; the application of this capability to measurement of striae will be explored.

Chris Evans is seen here checking the set up before measuring an optical element for a lithography system.

Just as the commercial PMIs have inadequate accuracy for measuring the figure of state-of-the-art optics, NIST work has also shown that commercially available atomic force microscopes (AFMs) have the necessary resolution for finish measurement, but are insufficiently accurate. NIST has developed a calibrated AFM that can establish the traceability of optical surface finish measurements. The instrument has on-line calibration in the X and Y directions using laser interferometry that will ultimately be accurate to ±3 nm. A capacitance gauge will provide calibration in the Z-direction of ±0.1 nm, which, in turn, is calibrated off-line using laser interferometry. (See "Surface Metrology" program description.)

Measurement of as-chucked wafer flatness requires separation of chuck induced errors from wafer thickness variations. We are establishing reference optical instruments at NIST that will provide traceable measurements. Flatness can be measured on two instruments operating at 633 nm; XCALIBIR will be able to measure 300 mm flats directly. In the interim we developed a variant of the Ritchey-Common test which allowed the use of a spherical wavefront from a 100 mm aperture interferometer to measure flatness of 300 mm diameter artifacts.

Wafer thickness variation can be measured in a NIST-patented interferometer operating at 1.55 µm. A 300 mm commercial implementation of the system has been installed and new measurement procedures are now being developed.

In the area of SSD our approach is to focus on a model system - single crystal sapphire - which also has important applications in, for example, silicon-on-insulator electronics and missile optical systems. Because sapphire is transparent at visible wavelengths, it can be inspected using techniques that would also be appropriate for glasses - but because of its crystalline nature, it can also be tested by techniques such as X-ray topography and micro-Raman spectroscopy. In this area we are supporting specific military projects while developing broadly applicable knowledge of the causes and detection of SSD.

Our approach to SSD focuses on sapphire optics because it represents an important product applications group, the single-crystal based components, and accommodates a broad spectrum of inspection techniques. Single crystal optics include silicon-on insulator electronics, 193 nm ultraviolet stepper optics, and infrared anti-missile seeker systems. Sapphire is transparent at visible wavelengths, so it can be inspected using a wide variety of optical techniques that are also appropriate for glasses. Because of its crystalline nature, sapphire can also be tested by diffraction techniques such as neutron diffraction for bulk condition, transmission electron microscopy and coherent X-ray topography for surface integrity. While we are filling specific and immediate defense needs, while also developing a broadly applicable knowledge of the hazards, causes detection, and possibly cures for SSD.

At the limits of precision, or size, advanced users can minimize their uncertainties by realizing the unit in their own facilities and then implementing measurement strategies to give a defensible uncertainty budget, without reference to any "external" authority. In the specific case of large optics, we will support the National Aeronautics and Space Administration's (NASA's) development of an in-house capability to make traceable measurements on optics larger than 400 mm aperture at the NASA Marshall Space Flight Center.

Standards Participation

- ANSI/ASME B89: Dimensional Metrology
- ISO TC 172: Optics and Optical Instruments
- ISO TC 213: Geometrical Product Specifications

Accomplishments

- July FY1999 Developed and installed XCALIBIR.
- June FY1999 Developed and published a new version of the Ritchey-Common test for circular flats.
- June FY1999 Identified artifact in wind tunnel test methodology leading to premature failure of sapphire domes.
- April FY1999 Patented design of new infrared interferometer for wafer thickness variation measurement, contracted for commercial prototype now installed at NIST.
- April FY1999 Measured all end reflector optics for LIGO observatories.
- November FY1999 Measured optics for prototype extreme-ultraviolet (EUV) lithography system.
- June FY1998 Developed new algorithms for instrument error separation now in use at commercial optical companies.
- June FY1998 Correlated X-ray topography and polarized light microscopy for sapphire windows.
- June FY1998 Developed Calibrated Atomic Force Microscope (see “Surface Metrology” program.)
- May FY1998 Measured all “Pathfinder” optics for the LIGO project, including tests of coating induced distortions, with uncertainties of approximately 1 nm rms.
- June FY1997 Demonstrated use of X-ray topography to differentiate between bulk and surface strains in sapphire.